10. DREDGING

Dredging is a very costly operation and involves many uncertainties that affect project cost, including a realistic estimate of the total quantity of material to be dredged and characteristics of the material as they relate to the dredge production rate (the rate at which solids are dislodged at the dredging site and transported to the discharge point). Other factors also affect dredging costs. A pipeline dredge operating in a navigation channel may obstruct traffic unless special arrangements are made. Dredges normally operate 24 hours a day, and if the dredge site is in or near an urban area, noise may preclude night operation. Weather conditions may also limit operations under some circumstances.

Costs and potential environmental impacts are fundamental considerations in evaluating alternative dredging and disposal methods and disposal sites. Many factors must be considered in developing a dredging operation, including:

a. Determining the quantity of material to be dredged initially and the frequency and quantity of future maintenance dredging.
b. Sampling to determine the physical and chemical properties of material to be dredged to ensure that the appropriate type of dredge is used, to assess dredge production rates so that time and cost estimates are realistic, and to identify any pollutants in material to be dredged.
c. Selecting the appropriate dredge type and size, disposal method, and disposal area to ensure environmental protection.
d. Identifying adequate disposal areas for both initial and future maintenance dredging, considering the physical and chemical properties of the dredged material.
e. Long-term management of disposal sites to maximize storage volume and beneficial use after the sites are filled.

Dredging for navigation channels is categorized as either initial new construction or maintenance dredging to restore authorized channel dimensions (depths and widths), as follows:

a. Initial construction dredging is dredging to authorized channel dimensions plus an allowance for overdepth dredging to compensate for inaccuracies in the dredging operation.
b. Periodic maintenance dredging is dredging performed on a regular basis, for example annually following the major flood season, to restore authorized dimensions, with the expectation that authorized dimensions will be maintained by the river until the next flood season.
c. Aperiodic or occasional maintenance dredging is done on an "as needed" basis when channel dimensions have diminished to where they limit navigation.

The objective of maintenance dredging is to provide authorized project depth and width at all times in the navigation season. In general, most maintenance dredging in inland waterways is required after river stages fall rapidly on the recession of flood hydrographs, when velocities decrease and coarser sediments are deposited. To minimize delays to shippers, dredging equipment (both government-owned and privately-owned under contract) is available to move quickly to shoaled areas. Priorities in maintenance dredging usually provide that when a number of crossings have shoaled to where navigation is affected, the shallowest crossings are dredged first (when this can be done without excessive movement of dredging plant). This increases usable depth throughout the waterway, and navigation benefits immediately.

In some cases maintenance dredging includes dredging beyond authorized dimensions for "advance maintenance" in critical, fast-shoaling areas, Figure 10.1. Such over-depth dredging can result in lesser overall dredging costs and increases reliability of project depth.

Shoaling and maintenance dredging can be reduced by operating criteria to gradually decrease flood control releases from reservoirs on hydrograph recession. For example, eleven of the upper Arkansas River basin reservoirs are operated to minimize shoaling problems downstream of the navigation locks and dams on the Arkansas River while meeting criteria for releases for flood control, hydropower, and recreation. The operating criteria are complex and are related to season of the year, storage in the flood control space of each reservoir, and storm location and magnitude. The reservoirs are operated so that flood releases gradually taper off on the recession of flood hydrographs and specific targeted rates of discharge reduction are attained at the Van Buren gage. As flood releases drop from 105,000 to 75,000 cfs and from 75,000 to 40,000 cfs, the decrease in flow is limited to not more than 20,000 cfs in 24 hours. From 40,000 to 25,000 cfs, the target taper is a uniform decrease in flow over a 21-day period.

Maintenance dredging can also be reduced by hinged pool operation, as discussed later in this section and in Appendix B.

10.1 Arkansas River Dredging

Alluvial rivers typically follow a meandering, shifting alignment and are wide and shallow. Canalization of such rivers generally requires channel rectification and stabilization work, as well as the construction of navigation locks and dams, to develop a stable channel of adequate navigable depth. Channel training structures are used to modify the curvature of sharp bends and reduce the tendency of the river to shoal in crossings, Figure 10.2. Cutoffs are constructed to eliminate bends of small radius that would be difficult or hazardous for commercial traffic. Such cutoffs usually involve excavating a pilot channel (sometimes by dredging) of small cross section that is widened by action of the river, Figure 10.3. The old bendway is cut off at the upstream end by a closure structure to prevent sediment deposition in the old channel, but remains open at the lower end for recreation access and environmental enhancement.

The lower Arkansas River, in Arkansas, carried a heavy sediment load prior to construction of the Arkansas River navigation project which includes large upstream multipurpose reservoirs that trap much of the sediment load previously transported to the lower river. These reservoirs and stabilization and rectification works were essentially complete prior to construction of Dardanelle Lock and Dam, one of three locks of medium lift (54 ft) on the lower river, Figure 10.4. The upstream reservoirs had already significantly decreased the natural sediment load when construction of Dardanelle was begun in 1959.

Under preproject conditions, the suspended sediment load at Dardanelle averaged 100.4 million tons per year; this was estimated to be reduced to 16 million tons per year under project conditions. It was expected that about 60 percent of the sand load entering Dardanelle reservoir would be deposited in the reservoir, but that 90 percent of the silt/clay load would pass through. In the 13-year period 1965-1977 the average suspended sediment inflow to Dardanelle was about 8 million tons per year, and sediment outflow averaged about 3.5 million tons per year in the period 1964-1981. Operating criteria for the low-lift dams provide for spillway gates to be opened as rapidly as possible on rising stages so that essentially open-river conditions prevail at medium to high flows and the river will retain its sediment transport capacity.

Construction of the low-lift navigation dams began in 1963 with Locks and Dams 1 and 2. By 1968 all the navigation structures were under construction, and the project was completed to Little Rock in December 1968, to Fort Smith in December 1969, and to Catoosa-Tulsa in December 1970. The low-lift navigation dams were sited with the objective of minimizing maintenance dredging at the heads of the pools, and special contraction works were designed for reaches immediately downstream of the locks and dams to aid in providing suitable depths and slopes so as to minimize loss of sediment-transport capacity below the structures.

Pools 9 through 2 downstream from Dardanelle Dam have very different characteristics at normal pool level with regard to:

a. Storage, ranging from 110,000 ac ft at Pool 2 to 32,000 ac ft at Pool 8.
b. Pool length, ranging from 33.2 miles at Pool 2 to 15.8 at Pool 3.
c. Surface area, ranging from 10,500 acres at Pool 2 to 3700 at Pool 3.
d. Average pool depth, ranging from 12.4 ft at Pools 3 and 4 to 7.6 ft at Pool 8.
e. Relationship of normal pool level to the 10,000 cfs flow line.
f. Minimum discharge at which all spillway gates are fully open, ranging from 80,000 cfs at Dam 8 to 280,000 cfs at Dam 2.

All these factors affect the efficiency of stabilization and rectification work in providing a stable navigable channel of adequate depth.

There was significant initial dredging as a part of project construction at the heads of Pools 9 through 2, including 17 million cu yds in Pool 9 immediately below Dardanelle Dam, to hasten development of an equilibrium degraded channel that would provide navigable depth with a minimum of maintenance dredging and meet the scheduled dates for initiating navigation.

Almost all maintenance dredging of the lower Arkansas River has been in the heads of the low-lift pools, at the approach to the next lock upstream, in relatively-long straight reaches, reaches of flat curvature, and long crossings. Except for Pool 2, the bulk of the maintenance dredging was in the early years of project operation prior to 1976. Shoal areas at the head end of Pool 2, Figure 10.5, are representative of areas requiring maintenance dredging. Pool 2 has had the highest rate of dredging of all pools and accounted for 36, 63, and 72 percent of all maintenance dredging in Arkansas in 1973, 1986, and 1993, respectively.

Additional contraction was added in some reaches of the pools after the project went into operation to minimize maintenance dredging and provide more reliable navigable depth. The authorized channel depth in the Arkansas River is nine feet; authorized channel width is 250 ft at project depth.

Maintenance dredging was negligible in the 1978-1984 period in Pools 9 through 3, averaging about 150,000 cu yds per year. Studies indicated that deposition in Pool 2, where maintenance dredging averaged 430,000 cu yds per year in the 1978-1984 period, is probably more related to pool characteristics than to design of the stabilization and contraction works. Pool 2 is significantly longer and has more storage at normal pool level than Pools 9 through 3, and it is subject to open-river flow conditions more rarely than the other pools (spillway gates fully open about once in seven years, on the average, compared to annually at the other pools) (Petersen and Laursen, 1986).

Schmidgall (1981, 1985) examined maintenance dredging on the Arkansas River as related to streamflow and concluded that the amount of dredging required in most pools is related to volume of flow. His data relating annual maintenance dredging in the State of Arkansas (the lower reach of Pool 13 through Pool 2) to annual streamflow at Van Buren are shown in Figure 10.6a. His data for the total system for 1969 through 1994, shown in Figure 10.6b, indicate that maintenance dredging has decreased significantly with time.

Cumulative dredging volume from when the project became operational in 1969 through 1984 is shown in Figure 10.7 for two reaches: Pools 9 through 3 and Pools 9 through 2. Data in the figure indicate that, if one disregards dredging in Pool 2 (on the basis that it is atypical of pools downstream of Dardanelle), annual dredging decreased significantly with time over the period of study, and was at a relatively constant and negligible rate of 780 cu yds per 100,000 ac ft of flow (or 150,000 cu yds per year) for the period 1978-1984. The data also clearly suggest that deposition problems in Pool 2 are of a different order of magnitude (and probably of different origin) than those in Pools 9 through 3.

Maintenance dredging on the Arkansas is initiated whenever depths in the navigation channel become less than the authorized 9-ft depth. Typically, maintenance dredging is to a depth of 12 ft, including 3 ft of overdepth dredging for advance maintenance to allow a time period for sediment buildup before the 9-ft authorized depth is no longer available and maintenance dredging must be repeated. The objective is to provide authorized navigable depth 100 percent of the time to the extent feasible. Dredging typically begins on the hydrograph recession at flows in the order of 120,000 to 70,000 cfs (flows that carry a significant sediment load with depths considerably in excess of authorized depth) to minimize potential interruption of navigation.

The Little Rock District awards two maintenance dredging contracts in January each year for work in the calendar year, and contracts run concurrently. Two cutterhead dredges are used, one assigned to Russellville (Dardanelle area) and the other assigned to Pine Bluff, but both work in any area of the river, as needed. In the period 1979 through 1989 (including three years in which the flow volume exceeded 30 million acre-ft), dredging in Arkansas ranged from 329,000 yds^3/yr in 1980 to 5,953,000 in 1988 and averaged 1.94 million yds^3/yr. In the period 1984 through 1994 (including six years in which the flow volume exceeded 30 million acre-ft), dredging in Arkansas ranged from 1,314 million yds^3/yr in 1984 to 4,785 in 1988 and averaged 2.27 million yds^3/yr.

10.2 Mississippi River Dredging

The Mississippi River has a navigable length of 1811 miles. Authorized channel dimensions are 9 by 150 ft from miles 857.6 to 853.4; 9 by 200 ft from miles from 853.4 to 815.2; and 9 by 300 ft downstream through the Vicksburg District. (Mileage above the mouth of the Ohio River at Cairo is measured as "miles above Cairo;" mileage below the confluence with the Ohio is measured as "miles above Head of Passes" at the mouth of the Mississippi River.) The river is canalized downstream to the vicinity of St. Louis, Figure 10.8.

The St. Paul District, Corps of Engineers, is responsible for the Upper Mississippi River downstream to below Lock and Dam 10 (mile 857.6 to mile 614). Dredging is accomplished with a 24-in cutterhead dredge owned by the District (and loaned for work in other Districts as well) and through annual one-year contracts with firms using mechanical draglines. In the 1975-1989 period, maintenance dredging averaged 750,000 cu yds per year, 600,000 by the cutterhead dredge and 150,000 by contract.

The Rock Island District of the Corps is responsible for the Upper Mississippi from just below Lock and Dam 10 to just below Lock and Dam 22 (mile 614 to mile 300). Most maintenance dredging is accomplished using the 24-in cutterhead dredge owned by the St. Paul District. In the 1986-1989 period, maintenance dredging averaged 570,000 cu yds per year. In 1989, 572,000 cu yds of material was removed from nine sites with the cutterhead and 29,400 cu yds were removed mechanically by dragline and clamshell dredges under contract.

The St. Louis District overseas the river from just below Lock and Dam 22 downstream to the mouth of the Ohio River (mile 300 to mile 0). There are four navigation locks and dams in the upper 100 miles of this reach, and open-river navigation prevails downstream. In the past up to 12 dredges were used in the St. Louis District for maintenance dredging, but currently only two are used routinely. One is a dustpan dredge owned by the District that usually works in the open-river reach. A cutterhead dredge is under contract from a private firm to dredge the navigation pools. The contracts are for one year and are paid on a per-cu-yd basis. Typically, $7 million to $8 million is spent on dredging each year (at $0.,75 to $1.00 per cu yd). However, because of the severe drought and record low stages in 1988 and 1989, approximately $23 million was spent in each year, and six additional dredges were required. Four were contracted from private firms, one was borrowed from the Memphis District, and one was borrowed from the St. Paul District (Derrick, 1991).

The Memphis District oversees the river from the confluence of the Ohio and Mississippi Rivers (mile 953.8) downstream to the mouth of the White River (mile 599). In the 1985-1989 period, maintenance dredging averaged 28.2 million cu yds per year. Work is accomplished by four dustpan dredges, three of which are Corps-owned and one under a year-round rental contract. These dredges are used where needed in the St. Louis, Memphis, Vicksburg, and New Orleans Districts.

The Vicksburg District is responsible for the reach of the Lower Mississippi River from the mouth of the White River downstream to just above the Old River Control Structure (mile 599 to mile 320.6). The Vicksburg District uses a combination of revetments, dikes, and dredging to maintain the navigation channel. From 1984 to 1989 an average of 2,285,000 cu yd of material was dredged each year. Most dredging is performed using two dustpan dredges, one owned by the District (and on loan to New Orleans District much of each year) and the other under a year-round contract with a private contractor.

10.3 Missouri River Dredging

Construction of six mainstream dams on the upper Missouri River has reduced the average sediment load from 200 to 50 millions tons per year, with an increase in the percentage of sand load and a decrease in percentage of silt and clay load. The Missouri River is an open-river waterway, and there has been no maintenance dredging in the navigation channel above Rulo since 1969. In the Kansas City District, below Rulo, the channel is contracted by dikes and no dredging was performed between 1980 and 1988. However, severe drought necessitated reservoir releases to be cut back below normal levels in 1988, 1989, and 1990, and depths dropped to less than the authorized 9-ft project depth. Approximately $775,000 worth of dredging was done in 1988 and 1989 using a cutterhead dredge borrowed from the St. Paul District.

10.4 Red River Dredging

Five navigation locks and dams were recently constructed on the lower Red River, as discussed in Appendix B. Lock and Dam 1, Figure 10.9, was completed in the fall of 1984, and significant sediment problems were experienced at the lock shortly after the project went into operation. Channel expansion and flow separation created slack water conditions and eddies at the lock and dam. Studies indicated that structural measures were required to either reduce the amount of sediment deposition or relocate it into more manageable (more easily dredged) areas. These measures included construction of dikes in the upstream lock approach channel and raising the wall that separates the downstream lock approach from the main channel. Periodic deposition has still occurred after these modifications were made, but it is to a much lesser extent than previously and in areas that can be easily dredged.

An unusual aspect of the deposition at Lock 1 is that deposition has occurred in the vicinity of the miter gates, Figure 10.10. In 1990, Vicksburg District rented an 8-in submersible pump for trial use in removing sediment in the vicinity of the miter gates. The material removed was fine sand and silt that, when compacted, becomes very hard and difficult to remove. The pump was used at three locations. The first test site was an area about 85 ft wide by 12 ft in the downstream direction, and about 6 ft deep downstream from the lower miter gates where material had settled out during spring 1990 high water; material was removed to prevent problems in opening and closing the lower miter gates. The second test area was inside the lock just upstream of the lower miter gate, measuring 48 by 85 ft and about 4 ft deep. The material had been compacted by currents, and opening and closing of the miter gates made the material very dense and hard. Pump production rate at these two sites was about 60 cu yds per hr. The third test site was between the downstream guide wall and the "I" wall where the material was clean sand, and the production rate was about 300 cu yds per hour.

As a result of success with the leased pump, the Vicksburg District purchased a 10-in submersible pump in 1991. Neilans, et al. (1993) report that the pump was used about three times a year at each of the three lower locks on the Red River, taking between 2 and 3 days to remove the sediment buildup from each lock.

An advantage of the submersible pump is quick response time. When clearing is needed, the submersible pump can be deployed in about four hours if the District's towboat is available. Maneuverability of the submersible pump makes it particularly well suited for removing sediment around the miter gates because it can be positioned in corners and along walls without damaging either the lock or the equipment.

10.5 Effect of Hinged Pool Operation on Maintenance Dredging

Hinged pool operation is a spillway gate operational procedure designed to lower normal upper pool level at a lock and dam to increase velocities through the deeper downstream reaches of the pool, with the objective of decreasing maintenance dredging requirements by moving depositing sediments farther downstream in the pool and lessening deposition at the head of the pool, as discussed further in Appendix B.

Locks on the Arkansas River were designed for hinged pool operation and have upper miter gate sills set low enough for tows to enter the locks with the upper pool drawn down five feet below the normal navigation pool level. This drawdown at the dam decreases depths and increases velocities through the downstream reach of a pool, thus moving depositing sediments farther downstream into the deeper reaches of the pool. On flood recession, after most sediments have settled out, the normal navigation pool is re-established. Water depths over the sediments deposited in the downstream reach of a pool are adequate to support navigation without dredging.

Hinged pool operation has been tried at most Arkansas River dams with various degrees of success. In the most successful hinged pool operations, the water level was drawn down only 2 or 3 ft, rather than the full design drop of 5 ft. Good results were achieved in moving sediments through the navigation channel in the upper reaches of Dardanelle Lake during recession of the 1995 floods by using a 2-ft drawdown hinge.

10.6 Dredging Equipment

Modern dredge plant can be classified as either mechanical or hydraulic (or a combination of the two). Mechanical dredges lift the dredged material by means of diggers or buckets of various design, and hydraulic (suction) dredges pick up material by means of suction pipes and pumps.

Mechanical Dredges. Mechanical dredges remove loose soft or hard materials by a dipper or bucket of some type and usually operate in conjunction with disposal barges that are filled with the excavated material and then moved to a disposal site and emptied. Dipper and bucket dredges are similar in that both operate with the dipper and bucket at the end of a boom, but the dipper is rigidly attached to the boom and the buckets are suspended by cables, Figure 10.11. Bucket and ladder dredges dig the material out using a chain of buckets rotating around a ladder, with the buckets discharging onto a conveyer belt that moves the dredged material to the disposal barge or site. These dredges are not usually self-propelled, but are moved to the work site by a tow. They can maneuver in a limited area by using spuds (Figure 10.11.)

Hydraulic Suction Dredges. Hydraulic suction dredges are usually categorized according to the means of disposal of the dredged material (hopper, pipeline, and sidecasting dredges) or according to the means for picking up the dredged material (cutterhead, plain suction, and dustpan dredges).

- **Hopper dredges**, Figure 10.12, are deep-draft seagoing vessels used primarily for work in exposed harbors and shipping channels where traffic precludes use of stationary pipeline dredges. They are not used in shallow-draft waterways in the United States.

- **Sidecasting dredges** are self-propelled shallow-draft seagoing vessels designed for dredging from bar channels at small coastal harbors that are too shallow for hopper dredges and too rough for pipeline dredges to operate. A sidecasting dredge picks up bottom material through two suction pipes and discharges it directly overboard outside the channel prism through a discharge pipe.

- **Hydraulic pipeline dredges** draw a slurry of bottom material and water through a suction line and pump the slurry through a floating discharge line to the disposal site. They are of three types: dredges with a plain suction intake, dredges with a cutterhead at the forward end of the suction line to loosen material to be dredged, and dustpan dredges with jets in the head to loosen material.

Cutterhead dredges, Figure 10.13, are the most widely used type in the United States and are generally considered to be the most efficient and versatile (U.S. Army, Corps of Engineers, 1983). The cutterhead dredge has a rotating cutter around the intake end of the suction pipe and can dig and pump all types of alluvial materials and compacted deposits such as clay and hardpan. Suction pipe diameter ranges from 8 to 30 in.

Cutterhead dredges consist generally of a cutter, ladder, suction pipe, A-frame, H-frame, pumps, spud frame and spuds, and auxiliary equipment. The ladder carries the cutter, suction pipe, lubrication lines, and usually the cutter motor. Dredge ladders are from 25 to 225 ft in length, and the length of ladder determines maximum dredging depth. Dredging may be done to depths of 150 ft with standard ladders in light silty materials. The dredge is held in position or moved ahead with spuds, and the dredge operates by swinging about one spud with the head describing an arc, Figure 10.13d. As the swing is completed, the second spud is lowered, and the other spud raised to make a swing in the opposite direction, and the dredge advances forward.

For open-water disposal, only a floating discharge line is needed with a cutterhead dredge.. The floating discharge line is made up of sections of pipe from 30 to 50 ft long, each supported by pontoons. If land disposal is used, additional sections of shore pipe, usually 10 to 15 ft long, are also needed, Figure 10.14.

Dustpan dredges are self-propelled vessels designed for working in noncohesive material in rivers or sheltered waters with no significant wave action, Figure 10.15. Dustpan dredges have a wide, flared, flat mouth up to 30 ft across on a rigid ladder, and the dredge head is equipped with pressure water jets that loosen the bottom material and suction openings through which the dredged material and water are drawn into the suction line as the dredge is winched forward. Dustpan dredges cut a channel the width of the head and are limited to making relatively shallow cuts in repetitive passes over the shoaled area. They normally discharge into open water through a relatively short pipeline up to 1000 ft long; a longer disposal line requires a booster pump. They can readily be moved outside the navigation channel to let traffic pass.

10.7 Dredged Material Disposal

The Corps of Engineers has been involved in improving channels for navigation since 1824, and the first major program for increasing navigable depth by dredging was authorized in 1896 to provide a 9-ft channel from Cairo, Illinois, to the Gulf of Mexico. For many years the material removed in dredging operations was considered a waste material except when used as fill for commercial or industrial development or to fill in dike fields and old bendways in rivers. However, in recent years, the environmental effects of dredged material disposal has become highly suspect in the public view, and much controversy has ensued.

The major problems associated with disposal of dredged material are:

a. Ensuring availability of sufficient disposal area for initial and future maintenance dredging within a reasonable (economically feasible) distance of dredging operations.

b. Potential adverse environmental effects associated with disposal of dredged material, including increase in turbidity, resuspension of contaminated sediments, and decrease in dissolved oxygen.

Disposal of dredged material usually takes place in one of the following areas:

a. Open water.

b. Elsewhere in the river cross section, as in deep troughs in bends that greatly exceed required navigable depth, in old river bends that have been cut off, and in dike fields or landward of other rectification structures.

c. Dry land in diked disposal areas.

d. Marsh or wetland areas near the river, either with or without retention dikes.

There is increasing interest in the use of dredged material as a resource in the United States because the amount of material dredged each year continues to increase and increasing urbanization and industrial development near waterways and ports has made it difficult to locate new sites for dredged material disposal in many areas. Environmental regulations also have restricted both land and water disposal options. The cost of dredged material disposal has increased rapidly in recent years with greater distances from the dredging site to the disposal area and with environmental controls. Potential environmental impacts can be minimized by using the most suitable dredge type and dredge size and by careful monitoring and control of dredging and disposal operations.

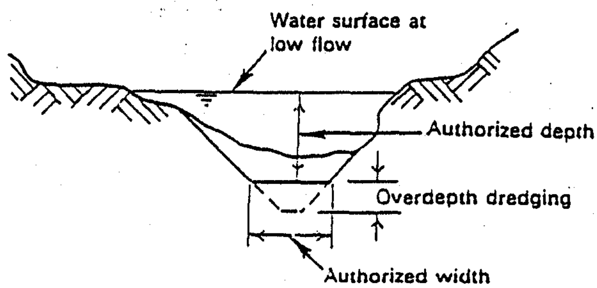


Figure 10.1. Authorized channel dimensions and overdepth dredging for advance maintenance.

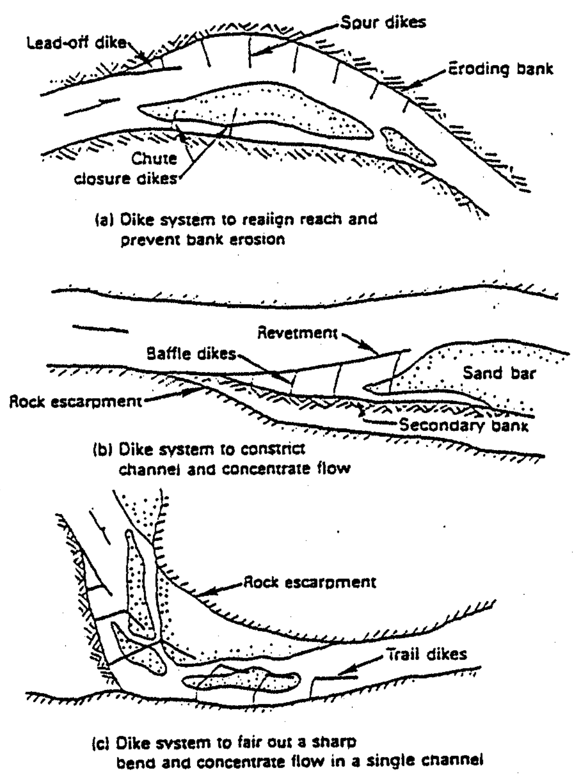


Figure10.2. Dike systems, Arkansas River Navigation Project

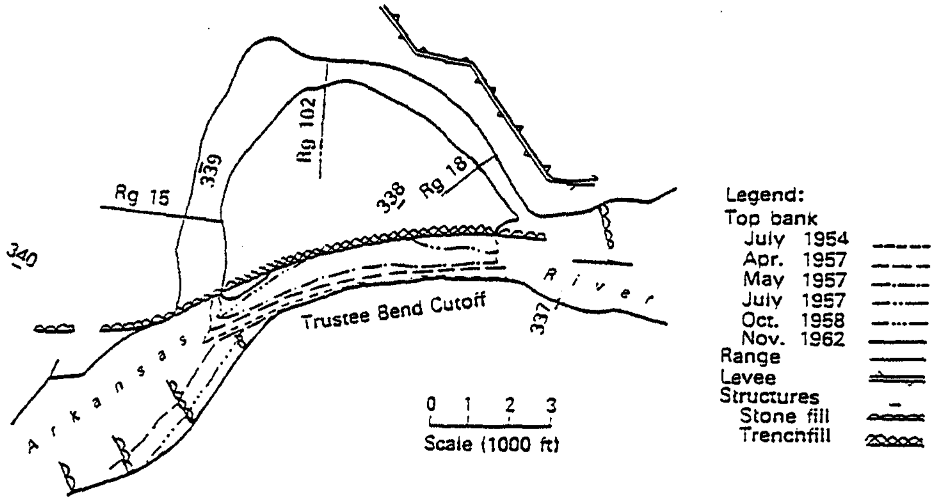


Figure 10.3. Trustee Bend Cutoff, Arkansas River Navigation Project (Corps of Engineers).

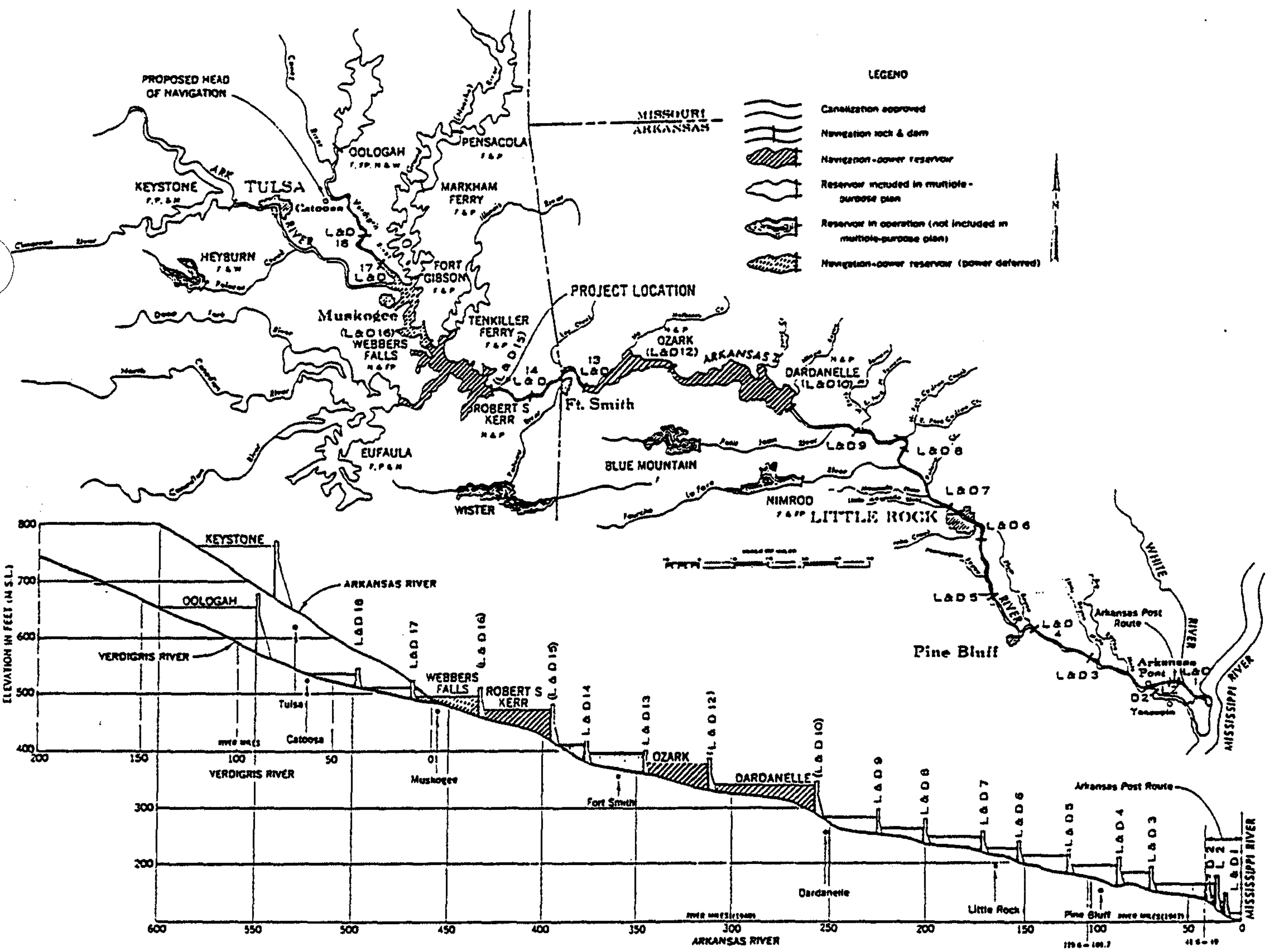


Figure 10.4. Arkansas River Navigation Project (Corps of Engineers).

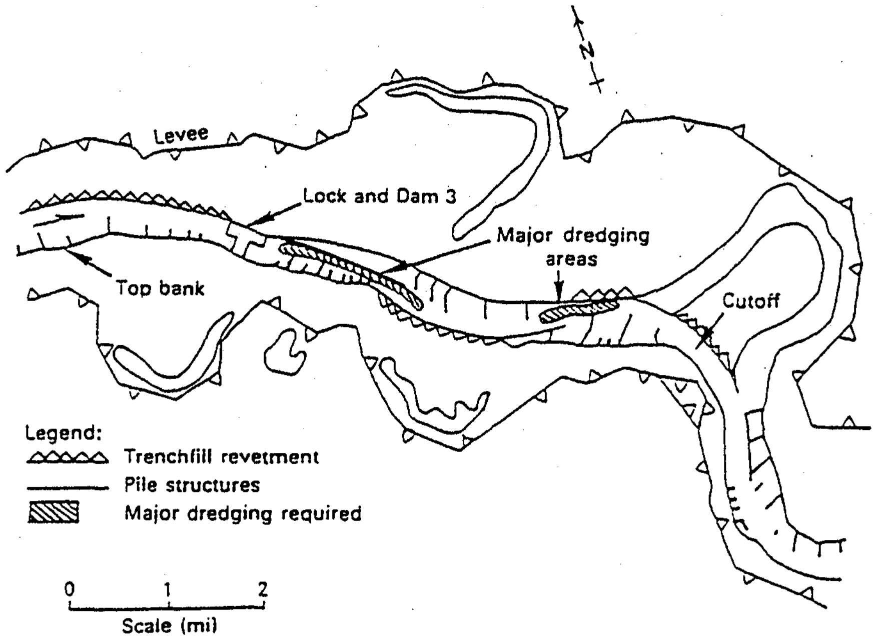


Figure 10.5. Major maintenance dredging reaches at head of Pool 2, Arkansas River Navigation Project (Schmidgall, 1972).

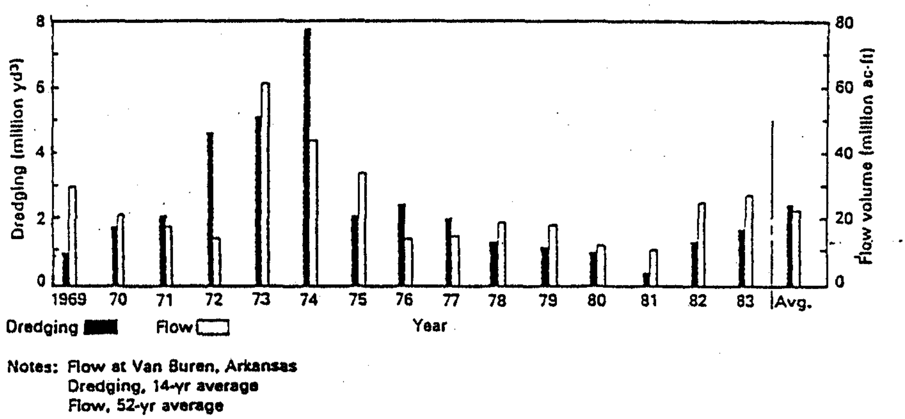
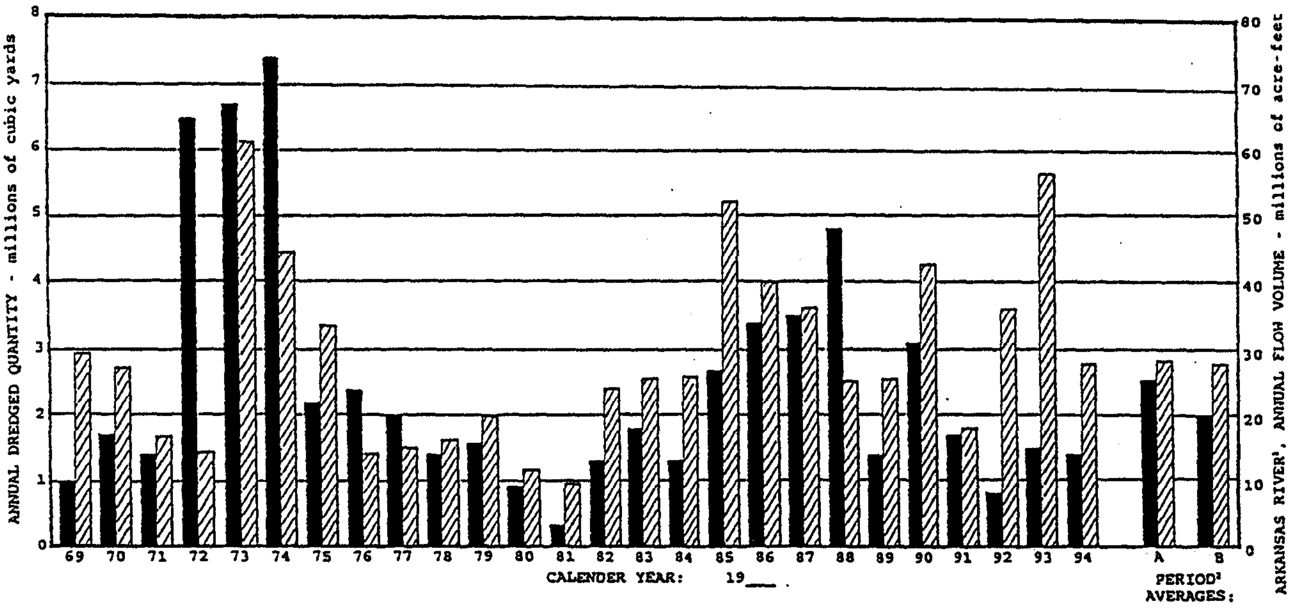


Figure 10.6a. Annual maintenance dredging in Arkansas and flow at Van Buren gage, Arkansas River Navigation Project (Schmidgall, 1981).



Dredging ■ Flow ▨

Dredging and flow averages
Period A. from 1969 through 1994.
Period B. from 1975 through 1994.

Figure 10.6b. Annual maintenance dredging in McClellan-Kerr Navigation System and flow at Van Buren gage (Schmidgall, 1995).

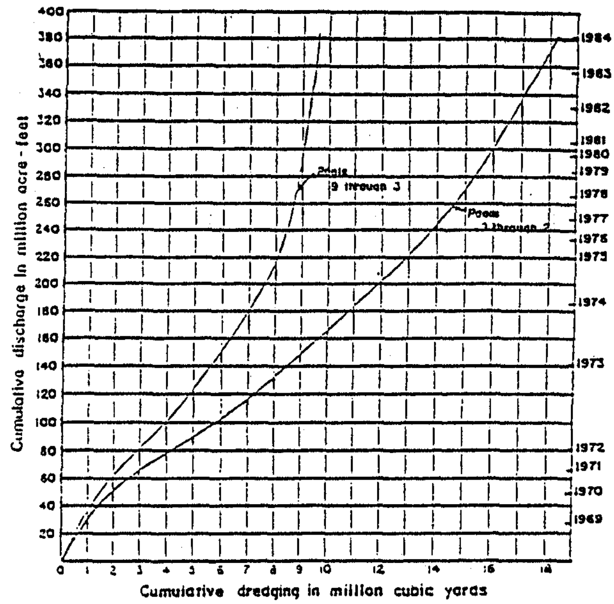


Figure 10.7. Cumulative dredging as a function of discharge, Arkansas River Navigation Project (Petersen and Laursen, 1986).

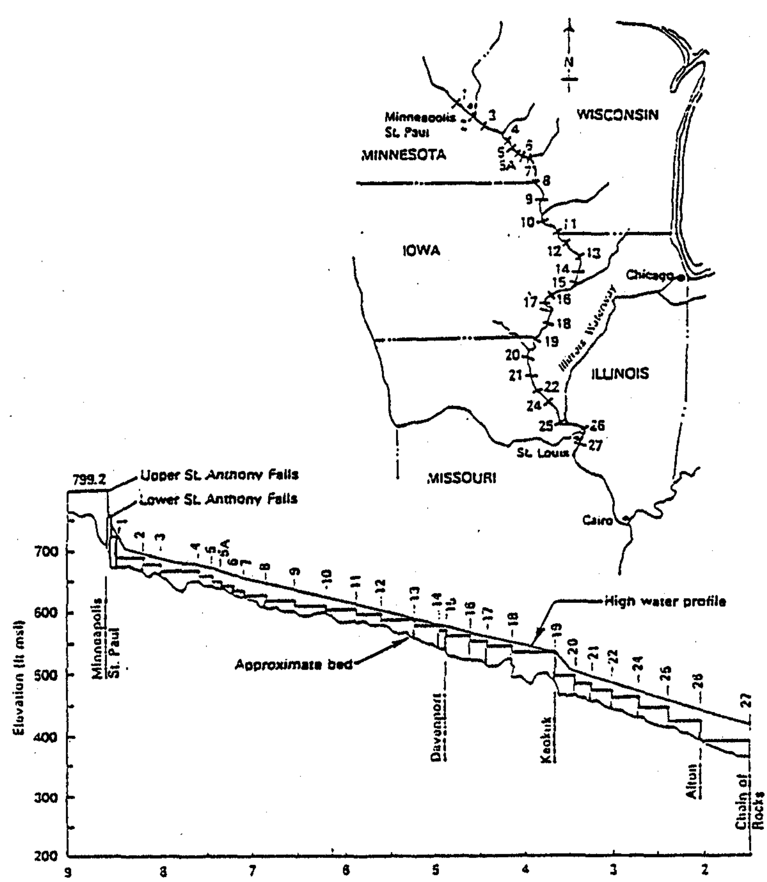


Figure 10.8. Upper Mississippi River Canalization Project (Corps of Engineers).

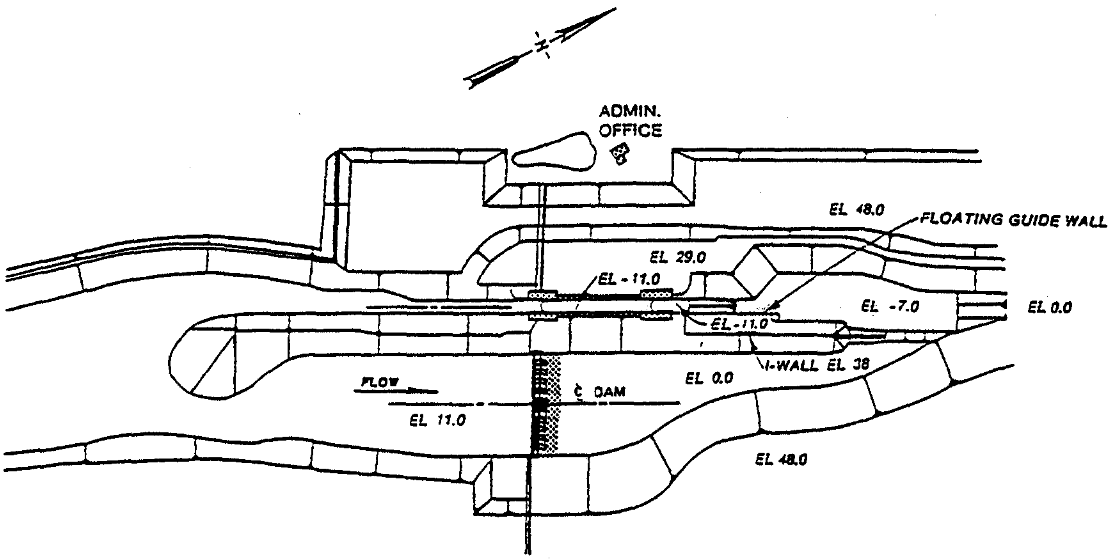


Figure 10.9. Lock and Dam 1, Red River Navigation Project, as constructed (Corps of Engineers).

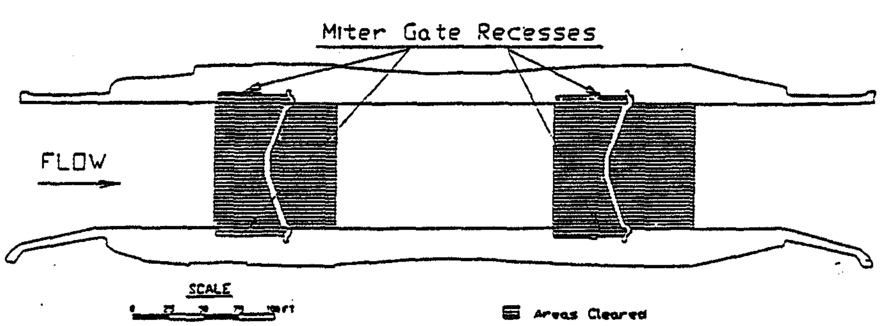
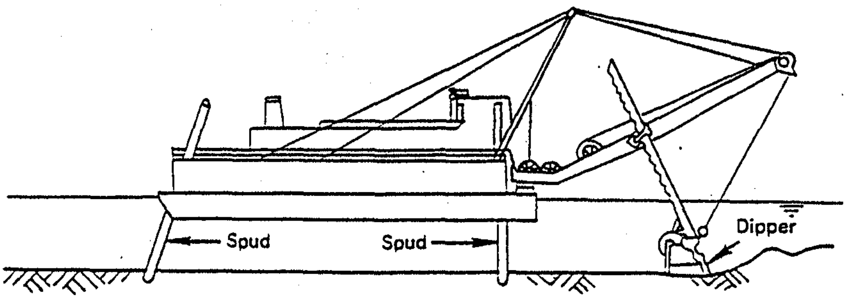


Figure 10.10. Areas cleared of sediment with submersible pump, typical lock, Red River Navigation Project (Neilans, et al., 1993).



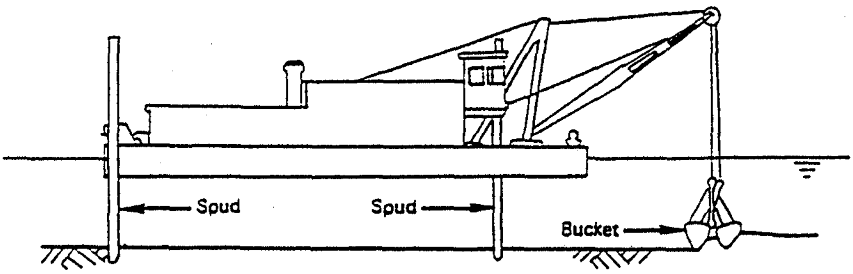


Figure 10.11. Types of mechanical dredges (U.S. Army, Corps of Engineers, 1983).

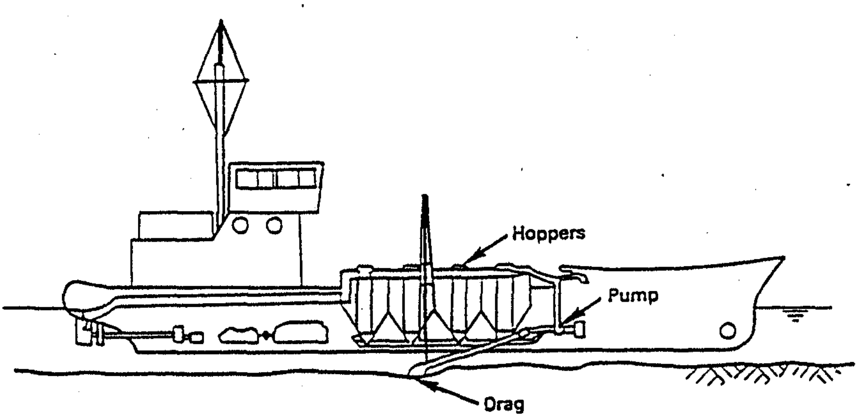
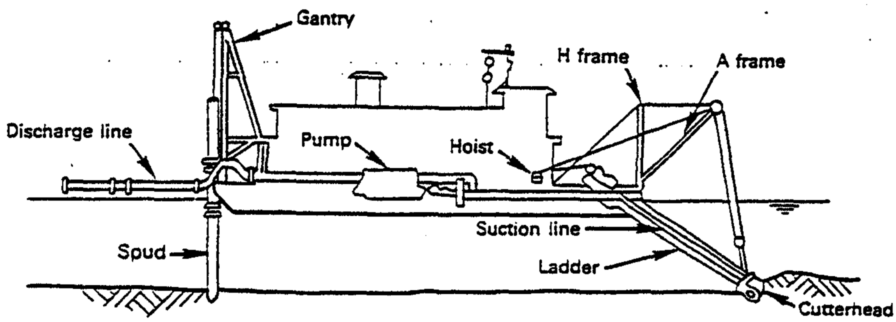
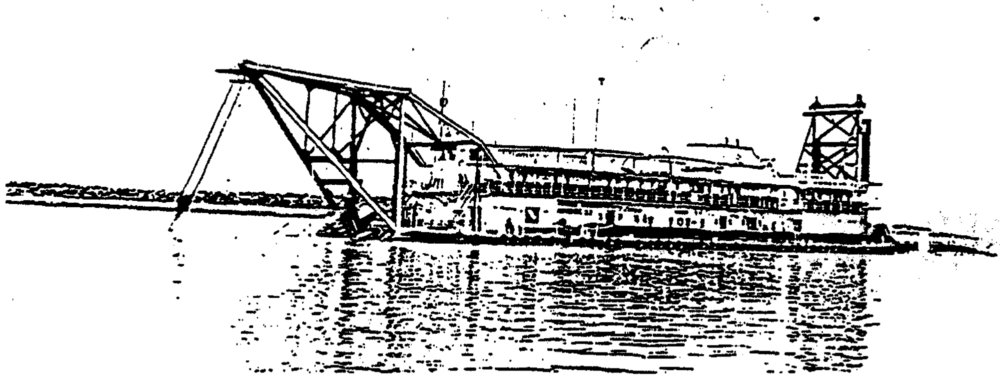


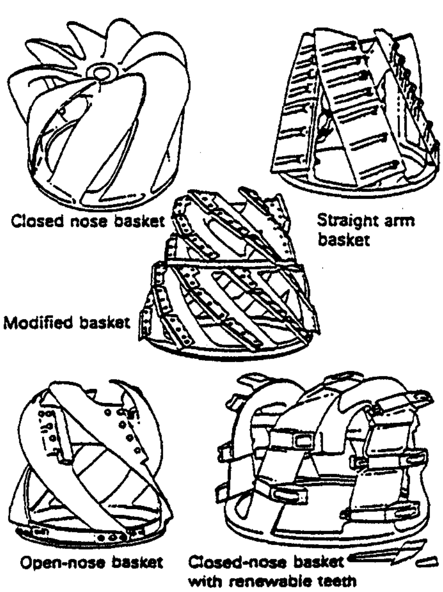
Figure 10.12. Self-propelled seagoing hopper dredge (U.S. Army, Corps of Engineers, 1983).



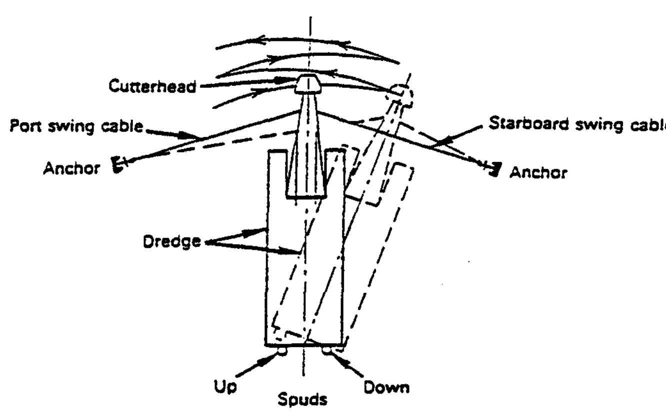
a. Hydraulic pipeline cutterhead dredge.



b. Cutterhead dredge 32, Bauer Dredging Co., with ladder submerged.



c. Types of cutterheads.



d. Operation of a cutterhead dredge viewed from above.

Figure 10.13. Cutterhead dredges (U.S. Army Corps of Engineers).

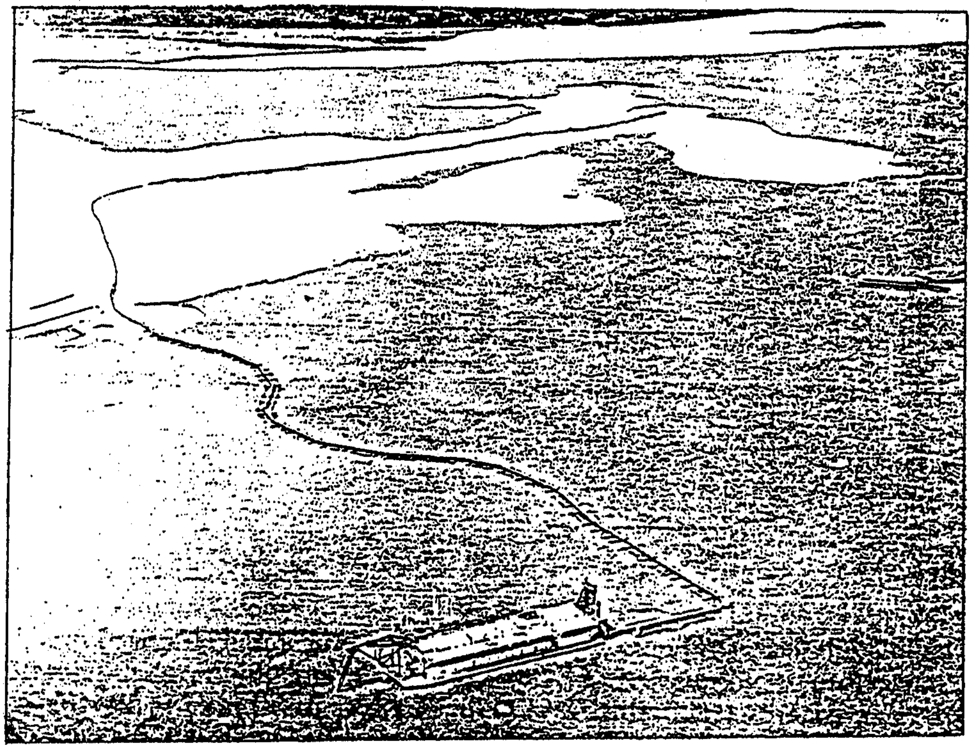


Figure 10.14. Pipeline cutterhead dredge with floating and shore discharge line, Lower Mississippi River (U.S. Army, Corps of Engineers).

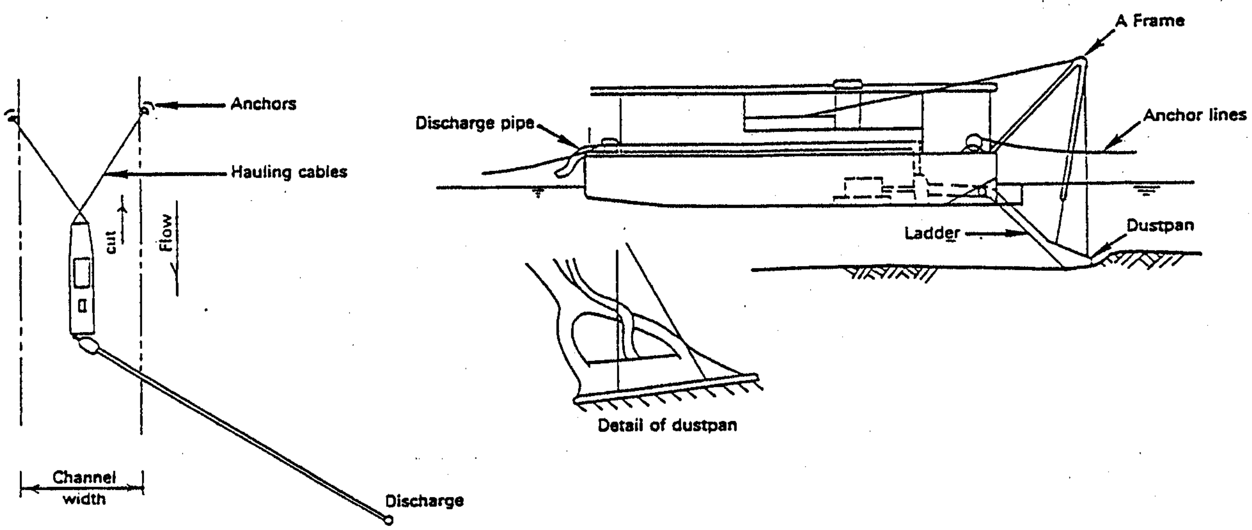


Figure 10.15. Dustpan dredge (U.S. Army, Corps of Engineers).